Abstract—Mobile infostation networks which achieve content distribution by exploiting the opportunistic contact among mobile users (MUs) and access points (APs) have attracted a lot of attention in the last few years. It is found that cooperation either between APs or MUs has a great impact on the network performance. However, in most of the existing works wherever cooperation is involved, cooperation among the APs or MUs is discussed independently, while few of them has jointly taken both levels of cooperation into account. In this paper, we propose a more general framework which allows two levels of cooperation. The benefit as well as the cost of such hierarchical cooperation are taken into consideration. With properly defined payoffs of both APs and MUs, each AP may gain more benefit by strategically forming coalition with other APs, while the MUs can also choose to cooperate with one another to further maximize their payoffs. To obtain the optimal structure of two-level cooperation, an implementable distributed algorithm is proposed. Through extensive numerical experiments, our scheme shows the high effectiveness in achieving the stable cooperation structure, and the impact of different system parameters is also extensively investigated.

Index Terms—Mobile infostation networks, coalitional game, network formation.

I. INTRODUCTION

While P. Gupta and P.R. Kumar give a pessimistic result on the capacity of wireless networks [1], mobile infostation model [1] provides a promising technique in achieving cost-effective content distribution in large-scale networks by employing the store-carry-forward data delivery fashion [2]. In mobile infostation networks, the node density is usually assumed to be sparse and there are one or more access points (APs) playing the role as the data sources. Each mobile user (MU) subscribes to one AP and content distribution can be achieved based on opportunistic contact between the MU and AP. In addition, cooperation either between APs or MUs is also widely used to improve network performance.

There is a rich body of literature on studying mobile infostation networks. While [2], [3] provide theoretical analysis of network delay and capacity, many other works focus on the performance evaluations of protocols and applications [4], [5]. In recent years, social property has also been investigated for the performance evaluations of protocols and applications [4], [5]. Without loss of generality, we assume one MU can subscribe to one AP. Let $\mathbb{H}_i$ denote the set of subscribers of $AP_i$, thus we have $\bigcup_{i \in \mathbb{H}} \mathbb{H}_i = M$. Fig. 1 shows an example of our network model with three APs and six MUs, and $\mathbb{H}_1 = \{MU_1, MU_2\}$, $\mathbb{H}_2 = \{MU_3, MU_4\}$ and $\mathbb{H}_3 = \{MU_5, MU_6\}$.

![Fig. 1. An example scenario of mobile infostation network.](image-url)

II. SYSTEM MODEL

A. Network Scenario

We consider a mobile infostation network which consists of $N$ APs and $M$ MUs. Let $\mathbb{N} = \{1, \ldots, N\}$ and $\mathbb{M} = \{1, \ldots, M\}$ be the sets of the APs and MUs, respectively. Two APs cooperate to form a coalition, then each of the APs can provide content dissemination service to the subscribers of the collaborated AP besides its own subscribers, while the MUs may also incentively cooperate with each other, i.e., download and relay content for other MUs. Specifically, we jointly consider the two levels of cooperation which can further reduce the data dissemination delay of the MUs, and meanwhile, the APs can also achieve higher payoffs.

The rest of this paper is organized as follows: In Section II, we provide a detailed description of the network scenario as well as the payoff function, which is a key part in our model. Our major contribution: the hierarchical cooperation formation is presented in Section III. Section IV presents the numerical results. Conclusion is given in Section V.

B. Payoff of the MUs/APs

As the MUs move, the inter-encounter interval between $MU_m$ and $AP_i$ is defined as the time period between two consecutive meetings of $MU_m$ and $AP_i$, which is assumed to be exponentially distributed with mean $1/\lambda_{mi}$ minutes [6],
where $\lambda_{mi}$ is the mean contact rate between $MU_m$ and $AP_i$. The inter-encounter interval between two MUs (i.e., $MU_m$ and $MU_n$) can be defined accordingly, which is also assumed to be exponentially distributed, with the mean of $1/\mu_{mn}$ minutes, where $\mu_{mn}$ is the mean contact rate between $MU_m$ and $MU_n$, here we have $\mu_{mn} = \mu_{nm}$. Note that both $\lambda_{mi}$ and $\mu_{mn}$ may vary over time, however, they change with a much larger time scale than that needed to disseminate data content, and thus we assume the values of $\lambda_{mi}$ and $\mu_{mn}$ keep constant in the following discussion.

We use $d_m(S_A, G_M)$ to denote the expected delay of $MU_m$, given the coalitional structure of the APs (i.e., $S_A$) and the cooperation formation of the MUs (i.e., $G_M$). Note that the formal definitions of $S_A$ and $G_M$ will be given in Section III-B and Section III-A, respectively. With a certain coalitional structure of the APs, it is assumed that only the subscribers of the APs in the same coalition are possibly willing to help each other. It is assumed that there are wired connection or broadband wireless links between each pair of APs, thus the content transmission between APs are counted out of the expected delay of the MU. Moreover, the content transmission time between a pair of MUs are considered to be much smaller when compared with the inter-encounter interval, thus it is also ignored in our model.

The payoff of $MU_m$ is defined as a function of $d_m(S_A, G_M)$ as follows:

$$u_m(S_A, G_M) = 1 - \frac{d_m(S_A, G_M)}{d_m^{\text{oc}}(S_A, G_M)} - C_i^A(G_M, \eta)$$  \hspace{1cm} (1)

where $d_m^{\text{oc}}$ is the expected delay of $MU_m$ when neither the APs nor the MUs cooperate. We use $C_i^A(G_M, \eta)$ to denote the cost of $MU_m$ for cooperating with other MUs, and the cost can be considered to come from spending energy on forwarding content to other MUs having cooperation relationship with $MU_m$. $\eta$ is defined as the cost for forming cooperation between a pair of MUs. In this case, if $MU_m$ has cooperation with more MUs, the cost to maintain the cooperation will increase. Note that if $MU_m$ cannot benefit from the cooperation among either the APs or the MUs, $d_m(S_A, G_M)$ will be equal to $d_m^{\text{oc}}$, resulting in a zero utility of $MU_m$.

The payoff of $AP_i$ is defined as the sum of payoffs of its subscribers, while the cost$^1$ of forming the coalition should be subtracted, which is denoted by $C_i^A$.

$$U_{AP_i}(S_A, G_M) = \sum_{m \in \mathcal{H}_i} u_m(S_A, G_M) - C_i^A(S_A, \sigma)$$  \hspace{1cm} (2)

Similarly, we use $\sigma$ to denote the cost for forming coalition with another AP, thus the larger the coalition size, the more cost each member has to undertake for maintaining such a coalition. It is assumed that there are wired connection or broadband wireless links between each pair of APs, thus the content transmission between APs are counted out of the expected delay of the MU. Moreover, the content transmission time between a pair of MUs are considered to be much smaller when compared with the inter-encounter interval, thus it is also ignored in our model.

C. Derivation of the Expected Delay

In the following part of this section, we describe how to obtain the expected delay with the knowledge of the cooperation relationship among the APs and MUs. Consider an example as shown in Fig. 1, if $AP_1$ and $AP_2$ have formed a coalition while $AP_3$ acts independently, $MU_1 - MU_4$ may form a cooperation network to forward content to each other, and $MU_1 - MU_4$ can obtain the desired content from both $AP_1$ and $AP_2$. Take $MU_1$ as an instance, it can directly obtain the content from $AP_1$ ($AP_2$) if it meets $AP_1$ ($AP_2$) first. As an alternative, $MU_1$ may also obtain the content from $MU_2 - MU_4$ if they would like to cooperate with $MU_1$. Suppose $MU_2$ intends to cooperate with $MU_1$, then $MU_1$ can obtain the content from $MU_2$ if $MU_1$ meets $MU_2$ first and at that time, $MU_2$ has already downloaded the content of $MU_1$ from $AP_1$ (or $AP_2$). It can be evidently seen that the diversity of the content circulating in the network is improved in this way. It can also be foreseen that the expected delay for $MU_m$ to get the required content will be reduced. The higher the content circulating diversity is, the lower the expected delay will be, this is the reason why the MUs can benefit from the cooperation among the APs.

Let $B_{12}$ denote the time needed for $MU_1$ to meet $MU_2$, then $Y_1 = X_{21} + B_{12}$ and $Y_2 = X_{22} + B_{12}$ represent the expected delay of $MU_1$ to meet $MU_2$ with the content previously obtained from $AP_1$ and $AP_2$, respectively. Note that $f_{X_{mi}}(t) = \lambda_{mi}e^{-\lambda_{mi}t}$, $i = 1, 2; m = 1, 2$. Without loss of generality, it is assumed that the mean contact rate differentiates from one to another. Thus both $Y_1$ and $Y_2$ are hypo-exponentially distributed variables. Then the expected delay of $MU_1$ should be the minimum value of random variables $X_{1j}, X_{12}, Y_1$, and $Y_2$. To obtain $d_m(S_A, G_M)$, we introduce the following theorem and propositions.

**Theorem 1:** Let $Z = \min\{X_{1i}, X_{2i}, \ldots, X_n, Y_1, Y_2, \ldots, Y_m\}$, where $X_i(1 \leq i \leq n)$ are exponentially distributed variables and $n$ is the number of such variables, $Y_j(1 \leq j \leq m)$ are hypo-exponentially distributed variables and $m$ is the number of such variables. Then the CDF of $Z$ can be calculated as:

$$F_Z(t) = P(Z \leq t) = 1 - \prod_{j=1}^{m} \left(1 - F_{Y_j}(t)\right) e^{-\sum_{i=1}^{n} \lambda_i t}.$$  \hspace{1cm} (3)

where $\lambda_i$ is the mean of random variable $X_i$, and $F_{Y_j}(t)$ is the CDF of random variable $Y_j$.

The theorem can be proved by applying the mathematical induction, which is not shown here due to the page limit.

III. Hierarchical Cooperation Formation Game

The structure of the hierarchical cooperation formation framework is similar to the Stackelberg game model. The APs and the MUs are considered as the leaders and followers, respectively. At the lower level, the MUs strategically establish a cooperation network to maximize their payoffs, given the coalitional structure of the APs. At the upper level, with the
knowledge of how the MUs will form cooperation network under the given coalitional structure of the APs, the APs will optimally decide how to form coalition to maximize their individual payoffs. We intend to find a stable cooperation structure that none of the APs nor the MUs will unilaterally change their strategies in order to achieve higher payoffs.

A. Cooperation among the MUs

First, we discuss the lower-level cooperation formation. Our aim is to design a complex loyalty distributed scheme for the MUs that wish to build a stable cooperation network structure among the MUs, specifying the set of MUs that MU_{m}(m = 1, \ldots, M) is willing to help, as well as that of MUs which can benefit from helping \(MU_{m}(m = 1, \ldots, M)\). We formulate the cooperation formation among the MUs as a network formation process, the participants of which are the MUs in \(\mathbb{M}\). Let \(V_{M}\) denote a mapping from an arbitrary cooperation network structure \(G_{M}\) to \(V_{M}(G_{M})\), which is a vector of payoffs that the MUs can achieve under network structure \(G_{M}\).

For ease of presentation, \(G_{M}\) can be represented by an undirected graph, where a link between two nodes implies the cooperation relationship between them. For instance, if \(MU_{m}\) and \(MU_{n}\) have formed a link, denoted by \(l_{m,n} \in G_{M}\), they are willing to help each other to forward contents. Let \(G_{M} + l_{m,n}\) denote the graph obtained by adding link \(l_{m,n}\) to the existing graph \(G_{M}\), where \(l_{m,n} \notin G_{M}\) and \(G_{M} - l_{m,n}\) denote the graph obtained by removing link \(l_{m,n}\) from the existing graph \(G_{M}\) where \(l_{m,n} \in G_{M}\), i.e., \(G_{M} + l_{m,n} = G_{M} \cup \{l_{m,n}\}\) and \(G_{M} - l_{m,n} = G_{M} \setminus \{l_{m,n}\}\) [7]. A cooperation link can be established only if the two end nodes of the link agree to collaborate with each other. However, any MU is assumed to have the discretion to unilaterally terminate cooperation relationships that they are currently involved in, so long as it can benefit more from breaking up with such relationships.

With the notions defined above, we apply the notion of pairwise stability proposed by Jackson and Wolinsky [7], and to obtain the pairwise stable network, we apply the distributed improving path method proposed by Jackson and Watts [7], which will be described in detail in Section III-C.

B. Cooperation among the APs

Then, we investigate the upper-level game, with the objective to form the most beneficial coalitional structure for the APs. The coalitional game for \(AP_{i}\) can be formulated as:

\[
\max_{S_{A}} U_{AP_{i}}(S_{A}, G_{M})
\]

s. t. \(\bigcup_{j=1}^{J} S_{A}^{j} = \mathbb{N}, S_{A}^{j} \cap S_{A}^{j'} = \emptyset \quad (j \neq j', 1 \leq j, j' \leq J)\)

where \(S_{A} = \{S_{A}^{1}, \ldots, S_{A}^{j}, \ldots, S_{A}^{J}\}\) is the coalitional structure of the APs, e.g., if \(S_{A}^{j} = \{\{AP_{1}, AP_{2}\}, \{AP_{3}\}\}\), then \(S_{A}^{1} = \{AP_{1}, AP_{2}\}\), and \(S_{A}^{2} = \{AP_{3}\}\). The number of possible coalitional structures for \(N\) APs is given by the Bell number \(D_{M}\), where

\[
D_{i} = \sum_{j=0}^{i-1} \binom{i-1}{j} D_{j}, \quad \forall i \geq 1, \quad D_{0} = 1. \quad (4)
\]

We use \(S_{A,x}\) to represent a certain coalitional structure of the APs. Consider the example shown in Fig. 1, the coalitional structures of three APs are defined as follows: \(S_{A,1} = \{\{AP_{1}\}, \{AP_{2}\}, \{AP_{3}\}\}, S_{A,2} = \{\{AP_{1}, AP_{2}\}, \{AP_{3}\}\}, S_{A,3} = \{\{AP_{1}, AP_{3}\}, \{AP_{2}\}\}, S_{A,4} = \{\{AP_{1}\}, \{AP_{2}, AP_{3}\}\}\) and \(S_{A,5} = \{\{AP_{1}, AP_{2}, AP_{3}\}\}\). Note that the number of possible coalitional structures will increase dramatically when the number of APs becomes large. To address this complexity problem, the approximation and reduction method proposed in [8] can be applied, which is not discussed in this paper.

The cooperation among the APs is formulated as a non-transferable-utility (NTU) coalitional game with \(G_{A} = (\mathbb{N}; V_{A})\), where \(\mathbb{N}\) is the set of players and \(V_{A}\) is a mapping from an arbitrary coalitional structure \(S_{A}\) to \(V_{A}(S_{A})\), which is a vector of payoffs the APs can achieve under coalitional structure \(S_{A}\). The decision of an AP to join or leave a coalition depends on how the payoff may vary. Given coalitional structure \(S_{A}\), the actions of \(AP_{i}\) can only fall into the following two categories [9]:

- **Splitting**: One coalition \(S_{A}^{j}\) in \(S_{A}\) can be partitioned into multiple coalitions \(S_{A}^{j+1}\), if the following condition is satisfied:

\[
U_{AP_{i}}(S_{A}^{j}) \geq U_{AP_{i}}(S_{A}), \forall i \in S_{A}^{j} = \bigcup S_{A}^{j+1}. \quad (5)
\]

Note that at least one of the inequalities should not be met with the equal sign.

- **Merging**: Multiple coalitions \(S_{A}^{j}\) in \(S_{A}\) may jointly agree to form a new single coalition \(S_{A}^{j+1}\), if the following condition is satisfied:

\[
U_{AP_{i}}(S_{A}^{j}) \geq U_{AP_{i}}(S_{A}), \forall i \in S_{A}^{j+1} = \bigcup S_{A}^{j}. \quad (6)
\]

Note that at least one of the inequalities should not be met with the equal sign.

![Fig. 2. Stable AP coalitional formation result.](image-url)
C. Proposed Distributed Algorithm

To achieve the stable hierarchical cooperation formation, a distributed algorithm based on the merge and split mechanisms and Jackson and Watts’s network formation method is presented in Algorithm 1. Note that $0 \leq \text{rand}() \leq 1$ is random number generator function, and $\varepsilon$ appearing in the algorithm denotes the probability of making irrational choice of the nodes.

Algorithm 1 Distributed hierarchical cooperation formation algorithm of APs and MUs in mobile infostation network.

1: Initialize iteration $t = 0$ and the coalitional structure of APs $S_A(t) = \{ \ldots, S_A^t, \ldots \}$
2: loop
3: repeat
4: Initialize $\tau = 0$, and cooperation network structure of MUs $G_M(\tau) = \{ \ldots, l_{m,n}(\tau), \ldots \}$
5: for $m \in M$ do
6: MU $m$ computes payoff $u_m$ from Eq. (1)
7: end for
8: Randomly identify a link $l_{m,n}$
9: if $l_{m,n} \notin G_M(\tau)$ then
10: if $(u_h(S_A(t), G_M(\tau) + l_{m,n}) > u_h(S_A(t), G_M(\tau))$
11: for both $h \in \{ m, n \}$ OR $(\text{rand}(\tau) \leq \varepsilon)$ then
12: $G_M(\tau + 1) \leftarrow G_M(\tau) + l_{m,n}$
13: end if
14: end if
15: if $l_{m,n} \in G_M(\tau)$ then
16: if $(u_h(S_A(t), G_M(\tau) - l_{m,n}) > u_h(S_A(t), G_M(\tau))$
17: for both $h \in \{ m, n \}$ OR $(\text{rand}(\tau) \leq \varepsilon)$ then
18: $G_M(\tau + 1) \leftarrow G_M(\tau) - l_{m,n}$
19: end if
20: end if
21: $\tau = \tau + 1$
22: until Steady cooperation structure of MUs is reached
23: for $i \in N$ do
24: AP$_i$ computes its payoff $U_{AP_i}$ from Eq. (2)
25: end for
26: Merge mechanism of the APs
27: if (Condition in Eq. (6) is satisfied) OR $(\text{rand}(\tau) \leq \varepsilon)$ then
28: Merge coalitions and $S_A(t + 1) \leftarrow S_A^t$
29: end if
30: Split mechanism of the APs
31: if (Condition in Eq. (5) is satisfied) OR $(\text{rand}(\tau) \leq \varepsilon)$ then
32: Split the coalition and $S_A(t + 1) \leftarrow S_A^t$
33: end if
34: $t = t + 1$
35: end loop

Note that similar methods to that proposed in [10] can be applied to analyze the stability of this algorithm. After a series of merge and split operations, the set of APs converges to a partition of disjoint coalitions, in which none of the coalitions has an incentive to perform further merge or split process. The convergence of any iteration composed of successive merge and split operations, as presented in Algorithm 1, is guaranteed as shown in [10]. There is another point we have to emphasize here is that, the proposed hierarchical cooperation formation framework actually consists of two stages. During the first stage, the APs and MUs form cooperation structures through an iteration of Algorithm 1 until termination. During the second stage, the content downloading procedure takes place under the stable cooperation structure obtained in the first stage.

IV. Numerical Results

In this section, we evaluate the performance of Algorithm 1 and investigate the impact of different system parameters on the stable cooperation formation result. Our numerical results are based on the network model shown in Fig. 1. $\varepsilon$ is set to be $10^{-3}$, $\sigma = 0.2$ and $\eta = 0.05$ by default.

Fig. 3. (a) Comparison of the APs’ payoffs under different coalitional structures, (b) Comparison of the MUs’ payoffs w/o forming cooperation network.

A. Stable Coalitional Structure of the APs

We first discuss the cooperation formation of the APs, obtained from using Algorithm 1. With the fixed MU-MU contact rates, we consider two cases with different MU-AP contact rates as shown in Fig. 2. To be representative, the first case describes a uniform scenario that the MUs have the same mean contact rate with all APs, while in the second case, subscribers of AP$_1$ may contact frequently with AP$_2$ and those of AP$_2$ may also contact with AP$_1$ frequently. Subscribers of AP$_3$ have high contact rates with AP$_1$, thus they may seldom need cooperation from AP$_1$ or AP$_2$. For a more comprehensive discussion, we vary the unit cost of forming coalition among APs (i.e., $\sigma$) and investigate the stationary probability distribution of the coalitional structures under different costs. Note that in our implementation, it is assumed that at most two coalitions can merge into a single coalition at one time. Similarly, one coalition can be split into at most two smaller coalitions at one time. This assumption is due to the consideration for reducing the complexity, we intend to remove this constraint and investigate the numerical results in our future work.

As shown in Fig. 2, it can be seen that in case 1, all APs will cooperate (i.e., grand coalition $S_{A,5}$ is formed) to provide content downloading service to their subscribers, when there is no cost for forming coalition or the cost is relatively low, i.e., below 0.2 in our example. However, as the $\sigma$ increases, each AP may only form coalition with one other AP at most. Since a uniform scenario is considered in case 1, it is expected to see that the variations of the stationary probabilities of coalitional structures $S_{A,2}$ – $S_{A,4}$ are nearly the same, as shown by the
overlapping curves in Fig. 2. As $\sigma$ continually increases to 0.7, the benefit of forming coalition among APs cannot balance the cost that has to be paid, therefore, all APs will choose to act independently.

In case 2, besides similar conclusions obtained for case 1, there are some important observations different from case 1: (1) Since subscribers of $AP_1$ and $AP_3$ have no regular contact with $AP_3$ and $AP_1$, respectively, the payoff improvement brought by the cooperation between these two APs may be relatively limited, thus the stationary probability of $S_{A,3}$ is always 0; (2) Due to the mean contact rate information in case 2, we may intuitively suppose that $AP_3$ and $AP_1$ are helpful to each other, while $AP_3$ should prefer to act independently or occasionally cooperate with $AP_2$. The simulation result perfectly coincides with such expectation. The advantage of $S_{A,2}$ can also be verified in Fig. 3(a).

### B. Stable Cooperation Network Formation of the MUs

Next, we discuss the cooperation network formation of the MUs, also obtained from using Algorithm 1. As shown in Fig. 4, for case 1, we take the grand coalition of the APs as an example to show how the MUs will form cooperation networks under a certain coalitional structure of the APs. While for case 2, we take $S_{A,2}$ as an instance, which is the dominating coalitional structure. Since the unit cost of MU cooperation (i.e., $\eta$) will evidently affect the formation of the cooperation network, we compare the network formation results when $\eta = 0.05$ and $\eta = 0.1$ for both cases.

In case 1, it can be seen that each MU will choose a partner to cooperate with at stable state when $\eta = 0.05$, as described by forming a link with another MU in the network graph. When $\eta = 0.1$, none of the MUs will cooperate with each other, resulting in an empty network. This is because MUs have already gain enough benefit from the APs’ grand coalition, and forming cooperation network among themselves will not provide further payoff improvement because of the high cost introduced by cooperation. In case 2, we have similar observations except some differences. Note that even when $\eta = 0.1$, the link between $MU_3$ and $MU_6$ always exists since $AP_2$ does not form coalition with either $AP_1$ or $AP_2$, which may stipulate their subscribers to persist in cooperating with each other for higher individual payoffs. When $\eta = 0.05$, the improvement of forming cooperation network among the MUs based on the coalitional structure of the APs can be illustrated by Fig. 3 (b). It can be seen that on the basis of the improvement brought by the coalitional formation of the APs, the cooperation network formed among the MUs can indeed bring further improvement of the individual payoffs of the MUs, so long as the cost needed to forming such a cooperation network does not overwhelm the benefit.

### V. Conclusion

In this paper, we have considered a hierarchical cooperation formation problem for mobile infostation networks. At the lower level, the MUs can intelligently form an optimal cooperation network to maximize their individual payoffs, given the coalitional structure of the APs. At the upper level, the APs can make full use of the knowledge about the MUs’ network formation strategies and optimally decide how to form coalition with each other. A distributed hierarchical cooperation formation algorithm has been proposed to solve this stackelberg-like problem and obtain the stable cooperation structure for both APs and MUs. The effectiveness of the algorithm has been extensively verified by the numerical results. Moreover, the impact of different system parameters on the stable cooperation structure has also been investigated.

### References