Evaluation of the Average Packet Delivery Delay in Highly-Disrupted Networks: The DTN and IP-like Protocol Cases

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***Abstract*—Delay/Disruption-Tolerant Networking (DTN) represents an innovative communication paradigm that enables the communication over Intermittently-Connected Networks (ICNs). ICNs are characterized by unpredictable or scheduled contacts among nodes, high latency, and high bit error rates. DTNs, unlike TCP/IP protocols, make use of store-and-forward techniques in order to cope with intermittent link issues. In this letter, a simple model is proposed to compute the average packet delivery delay in ICNs. Both the IP-like paradigm used by traditional TCP/IP protocols and DTN are considered. The results provide theoretical insights into the applications of these two approaches to ICNs. Numerical results and simulations are presented, too.**

***Index Terms*—Intermittently-connected networks, store-and-forward mechanism, IP networks, Markov chains.**

I. Introduction

THE last ten years have seen the emergence of applications where networks operate under conditions in which the assumptions of "universal connectivity" and "global information" about the network state do not hold. An example of such scenarios is represented by wireless sensor networks deployed in extreme regions [1]. They consist of low-power sensor nodes that, for the purpose of energy saving, periodically switch between active mode and sleep mode and thus are unable to continuously communicate with a data-collecting server. Other examples are mobile ad-hoc networks typically composed of nodes (e.g., smarthphones, Global Positioning System (GPS) navigation devices, and laptops) installed on continuously-moving objects (e.g., vehicles, individuals, and animals) [2], [3]. In such contexts, connectivity is intermittent and the existence of end-to-end paths between node pairs is not always guaranteed. Moreover, due to low power availability and energy saving, often some nodes shut down unexpectedly or enter into sleep mode. These actions imply frequent link disruptions. Networks with such characteristics are commonly called *Intermittently-Connected Networks* (*ICNs*) [4].

In order to cope with the challenging conditions of ICNs and to enable the proper operation and functionality of applications, a new networking paradigm has been proposed, known as *Delay/Disruption-Tolerant Networking* (*DTN*) [1]. By using long-term store-and-forward message switching, DTN overcomes the problems associated with intermittent connectivity, long and variable delay, asymmetric data rates, and high error rates. Of course, DTN is suitable for applications with no delay constraints. Whole messages are forwarded from a storage place on one node (DTN node) to a storage place on another node, along a path that eventually reaches the destination. The storage places can hold for a long time messages with no delay constraints (*persistent storage*), in contrast with the very short-term storage provided by memory chips typical of IP-based internet routers, which store incoming packets for few milliseconds/seconds. In order to transmit data, the IP-like paradigm requires the availability of a permanently available end-to-end path, whereas the DTN approach, by adopting the store-and-forward mechanism, is able to cope with intermittent connectivity and link disruptions. Data are sent to intermediate nodes where they are kept and sent to the final destination or to another intermediate node only when possible or convenient, without dropping messages for delay reasons.

In this letter, we investigate the average packet delivery delay in ICNs theoretically, when either DTN or the IP-like protocol is adopted. To the best of our knowledge, no theoretical results were previously available on such a comparison. Indeed, most literature on the comparison of the TCP/IP protocol suite and DTN is devoted to practical experimentations. The work [5] addresses pros and cons of TCP/IP to build the so-called Interplanetary Internet. In [6], the throughput performances of the Digital Smart Technologies for Amateur Radio are investigated with various IP and non-IP based protocols. The paper [7] presents a preliminary investigation of the disruption impact on the performances, by comparing different approaches such as end-to-end TCP, Performance-Enhancing Proxy (PEP) based on TCP splitting, and DTN. In our study we consider a single packet delivered from a source node to a destination node, transmitted on a single path. As in DTN the storage places can hold messages for a long time, we can suppose that the packet will be delivered to the destination at the end (see Section IV for possible extensions to multiple paths). Related works are [2], [8], [9], which consider a multi-copy routing approach. They suppose that transmission and propagation delays are negligible, whereas our study addresses also the more realistic case in which such time intervals have to be taken into account.

The paper is organized as follows. In Section II, we describe the adopted model for an ICN and provide the main theoretical contributions of the paper, i.e., Propositions 2.1 and 2.2. Section III presents numerical results derived by applying our theory and simulations based on the use of a discrete-event simulator. Section IV is a final discussion.

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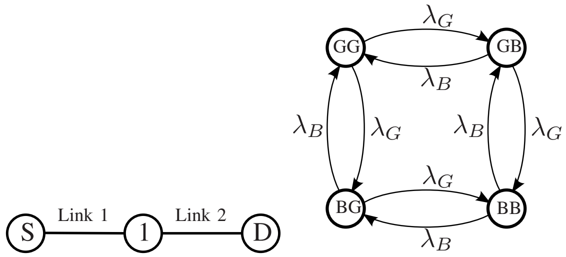


(a) Network topology. (b) The associated CTMC.

Fig. 1: A simple two-hop network topology (a) and the associated CTMC, whose nodes represent the sets of configurations of its links (b). The parameters λ_B and λ_G are the non-zero transition rates between different states of the CTMC.

II. The ICN Network Model

We consider the following ICN scenario. A number of mobile nodes is deployed in an area. The nodes follow a mobility model for which the following property holds: the inter-meeting time, as well as the contact time between two generic nodes, is an exponentially-distributed random variable. Popular mobility models for mobile ad-hoc networks (MANETs), such as Random Waypoint and Random Direction [2], enjoy such a property, as well as vehicular ad-hoc networks (VANETs) [3], [10], [11]. As a consequence of the exponential-distributed condition, the behaviour of the communication between each pair of nodes (in the following called *link*) can be viewed as a two-state *Continuous-Time Markov Chain* (*CTMC*). For each link, the configuration called *bad* (B) models the case in which the two nodes are not in contact (the link is disrupted and there is no connection at all), whereas the configuration *good* (G) represents the situation in which two nodes are in contact and are able to transmit the data (i.e., the link is operating). We denote by $\lambda_G > 0$ the transition rate of each link from G to B and by $\lambda_B > 0$ the transition rate from B to G. The average lifetimes of the two states G and B are $\tau_G = 1/\lambda_G$ and $\tau_B = 1/\lambda_B$, resp., whereas the corresponding stationary probabilities are $\pi_G = \tau_G/(\tau_G + \tau_B) = \lambda_B/(\lambda_G + \lambda_B)$ and $\pi_B = \tau_B/(\tau_G + \tau_B) = \lambda_G/(\lambda_G + \lambda_B)$.

We consider a single packet or message to be delivered from a source node to a destination node through a single path traversing intermediate nodes. We focus our attention on the case of an *L-hop network topology*, modelling a single path source-destination. The links are assumed to be independent and the state of the network is represented by the ordered L-tuple of the states (either G or B) of its links. As a simple example, Figure 1(a) shows the network topology for the case of $L = 2$ links and 3 nodes. The CTMC representing the states of the two links is depicted in Figure 1(b). The node GG represents the state in which both links are in the configuration G, whereas in GB the first link is in the configuration G and the second one in B. Similar explanations hold for states BB and BG. So, GB and BG in Figure 1(a) are two different states.

For DTN and IP-like paradigms, the next Propositions 2.1 and 2.2 provide expressions for the *average delivery delay* t_{DTN} and t_{IP}, resp., experienced by a data packet that needs to be transmitted, i.e., the average time from its generation by the source to its arrival at the destination. We assume that the packet generation process at the source node follows a Poisson process, so in the analysis we can exploit the *Poisson Arrivals See Time Averages* (*PASTA*) property [12]. We also suppose that the sum of transmission and propagation delays along each link is a constant $\Delta \geq 0$ (the limit case $\Delta = 0$ models the situation in which both are considered negligible delays).

Proposition 2.1: Given an L-hop network topology whose independent links have the same values of λ_G and λ_B and a constant value Δ for the sum of transmission and propagation delays, the average packet delivery delay in the DTN scenario is given by

$$t_{DTN} = L\left[\Delta + \frac{1 - p(\lambda_G, \Delta)}{p(\lambda_G, \Delta)}(\tau(\lambda_G, \Delta) + \tau_B) + \pi_B\tau_B\right], \quad (1)$$

where $p(\lambda_G, \Delta) := \int_\Delta^\infty \lambda_G e^{-\lambda_G x} dx$ and $\tau(\lambda_G, \Delta) := \int_0^\Delta x \frac{\lambda_G e^{-\lambda_G x}}{1-e^{-\lambda_G \Delta}} dx$. For $\Delta \simeq 0$, (1) simplifies to

$$t_{DTN} \simeq L\pi_B\tau_B\,. \quad (2)$$

Proof. In order to be able to successfully transmit a packet from one node to another, the associated link has to be in the configuration G for a time interval of length at least Δ. Let w_G be the average time necessary to traverse each link, assuming that the packet has arrived at the first end of the link and that the link is in the state G at the beginning of the transmission attempt. Since the lifetime of the configuration G is an exponential random variable with parameter λ_G, with probability $p(\lambda_G, \Delta) := \int_\Delta^\infty \lambda_G e^{-\lambda_G x} dx$ the link remains in the configuration G for the entire duration Δ of the packet transmission over the link. Otherwise, with probability $1 - p(\lambda_G, \Delta)$ the link moves to the configuration B before the end of the transmission, thus causing a failure. In this case, on average the packet has to wait a time $\tau(\lambda_G, \Delta) := \int_0^\Delta x \frac{\lambda_G e^{-\lambda_G x}}{1-e^{-\lambda_G \Delta}} dx$ (the denominator is due to the conditioning on the transmission failure event) plus the average lifetime τ_B in the link configuration B, before finding again the link in the state G. Starting from this instant, the packet waits on average w_G. Then, solving the resulting recursion we get

$$\begin{aligned} w_G &= p(\lambda_G, \Delta)\Delta + (1 - p(\lambda_G, \Delta))(\tau(\lambda_G, \Delta) + \tau_B + w_G) \\ &= \Delta + \frac{1 - p(\lambda_G, \Delta)}{p(\lambda_G, \Delta)}(\tau(\lambda_G, \Delta) + \tau_B)\,. \end{aligned}$$

By the PASTA property, the packet (when generated at the source node or at its arrival at each intermediate node) finds the successive link to be traversed either, with probability π_G, in the configuration G (so it needs on average w_G to traverse the link), or, with probability $\pi_B = 1 - \pi_G$, in the configuration B (in which case on average $\tau_B + w_G$ is required). Hence, the average time necessary to traverse each link is $\pi_G w_G + \pi_B(\tau_B + w_G) = w_G + \pi_B\tau_B = \Delta + \frac{1-p(\lambda_G,\Delta)}{p(\lambda_G,\Delta)}(\tau(\lambda_G, \Delta) + \tau_B) + \pi_B\tau_B$. Given L independent links, we get (1) multiplying by L the average time needed to traverse each link, and (2) by expanding (1) up to the first order in Δ. ■

To deal with the IP-like case, we order the 2^L states of the CTMC associated with the L-hop network topology in decreasing lexicographical order, starting from the state 1 in which all the L links are in the configuration G, and ending in the state 2^L in which all the L links are in the configuration B. For example, with $L = 3$ we have $\{$GGG, GGB, GBG, GBB, BGG, BGB, BBG, BBB$\}$. By π_i we denote the stationary probability of the i-th state of the CTMC and by q_{ij} the transition rate from the state i to the state j. By the link independence assumption, $\pi_i = \pi_G^{g(i)} \pi_B^{L-g(i)}$, where $g(i)$ is the number of links in the configuration G for the state i. For each pair of different states i and j of the CTMC, $q_{ij} \neq 0$ if and only if i and j differ in the state of one link only. More specifically, $q_{ij} = \lambda_B$ if that specific link moves from the configuration B in the state i to the configuration G in the state j, otherwise $q_{ij} = \lambda_G$ (see Figure 1(b) for $L = 2$). Moreover for $i = j$, we let (see [13])

$$q_{ii} := - \sum_{l \in \{1,\ldots,2^L\} \setminus \{i\}} q_{il} \,.$$

Finally, for the i-th state of the CTMC, we define the *expected first hitting time* k_i of the state 1 in which all the links are in the configuration G as the expectation of the first time at which the CTMC, starting from the state i, "hits" or visits the state 1. By an application of [13, Theorem 3.3.3], the vector of k_i's is the minimal non-negative solution the linear system

$$\begin{cases} k_i = 0, & \text{for } i = 1\,, \\ -\sum_{j=1}^{2^L} q_{ij} k_j = 1, & \text{for } i = 2, \ldots, 2^L\,. \end{cases}$$

By a symmetry argument, the states with the same number of links in the configuration B have the same value of the k_i's (e.g., $k_{2^0+1} = k_{2^1+1} = k_{2^2+1} = \ldots = k_{2^{L-1}+1}$, since the corresponding states have $L-1$ links in the configuration G).

Proposition 2.2: Given an L-hop network topology whose independent links have the same values of λ_G and λ_B and a constant value Δ for the sum of transmission and propagation delays, the average packet delivery delay in the IP-like scenario is given by

$$t_{IP} = L\Delta + \frac{1-p(L\lambda_G, L\Delta)}{p(L\lambda_G, L\Delta)} (\tau(L\lambda_G, L\Delta) + k_{2^L-1}) + \sum_{j=1}^{2^L} \pi_j k_j\,, \tag{3}$$

where $p(L\lambda_G, L\Delta) := \int_{L\Delta}^{\infty} (L\lambda_G) e^{-(L\lambda_G)x} dx$ and $\tau(L\lambda_G, L\Delta) := \int_0^{L\Delta} x \frac{(L\lambda_G)e^{-(L\lambda_G)x}}{1-e^{-(L\lambda_G)(L\Delta)}} dx$. For $L\Delta \simeq 0$, (3) simplifies to

$$t_{IP} \simeq \sum_{j=1}^{2^L} \pi_j k_j\,. \tag{4}$$

Proof. In order to be able to successfully transmit a packet from the source to the destination, in the IP-like scenario, all the L links need to be simultaneously in the configuration G for a time interval of length at least $L\Delta$. Let w_1 be the average time necessary to traverse the sequence of links, assuming that all the links are in the configuration G at the beginning of an attempt of transmission. Proceeding similarly to the proof of Proposition 2.1, we get

$$\begin{aligned} w_1 &= p(L\lambda_G, L\Delta)(L\Delta) \\ &\quad + (1-p(L\lambda_G, L\Delta))(\tau(L\lambda_G, L\Delta) + k_{2^{L-1}+1} + w_1) \\ &= L\Delta + \frac{1-p(L\lambda_G, L\Delta)}{p(L\lambda_G, L\Delta)} (\tau(L\lambda_G, L\Delta) + k_{2^{L-1}+1})\,, \end{aligned}$$

where $L\lambda_G$ is the mortality rate for the state 1, and $k_{2^0+1} = k_{2^1+1} = k_{2^2+1} = \ldots = k_{2^{L-1}+1}$). So, by the PASTA property we have $t_{IP} = \sum_{j=1}^{2^L} \pi_j (k_j + w_1) = w_1 + \sum_{j=1}^{2^L} \pi_j k_j$. ■

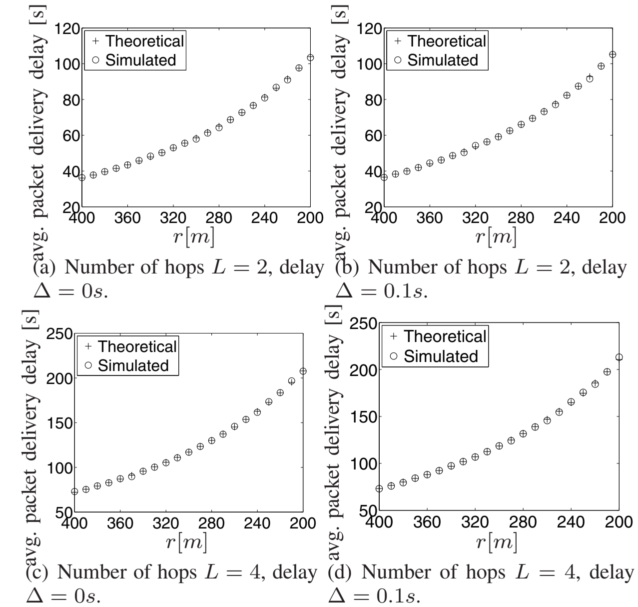
III. Numerical Results

In this section, we compare the performances of the IP-like and DTN approaches, both numerically, via formulas (1) and (3) provided by Propositions 2.1 and 2.2, resp., and by using an event-driven ad-hoc simulator written in C++, under various levels of network disruption. We consider the following scenario. The nodes move according to a random waypoint mobility model in a square of size $1km^2$ with speed chosen uniformly in $[14.5, 36]m/s$ (with average speed between two nodes $\sim 30m/s$). The *transmission radius* r of the nodes (i.e., the largest inter-node distance under which the associated link is in the configuration G) varies from $400m$ to $200m$, thus determining values of λ_B from ~ 0.0328 to ~ 0.0164 and λ_G from ~ 0.0478 to ~ 0.0955 (computed by using the formulations in [2], [14]). We vary also the number L of hops and the value Δ of the sum of transmission and propagation delays.

Figure 2 shows the comparison of theoretical (with the "+" mark) and simulated curves (with the "o" mark) of the DTN average packet delivery delay for two values of the number L of hops and the transmission radius r. When r decreases, the network becomes more disrupted and the average packet delivery delay increases. When the number of hops increases, the delivery delay increases as well in a proportional way, as indicated in Eq. (1). This can be also observed from the shape of the curves in Figures 2(a)-(d). Note that the increase of the sum Δ of the transmission and propagation delays does not heavily impact the delivery delay. Indeed, with $L = 2$ and $r = 200m$ the delivery delay difference between the cases $\Delta = 0.1s$ and $\Delta = 0s$ is about $1.3703s$, whereas the same difference when $L = 4$ is about $2.7406s$.

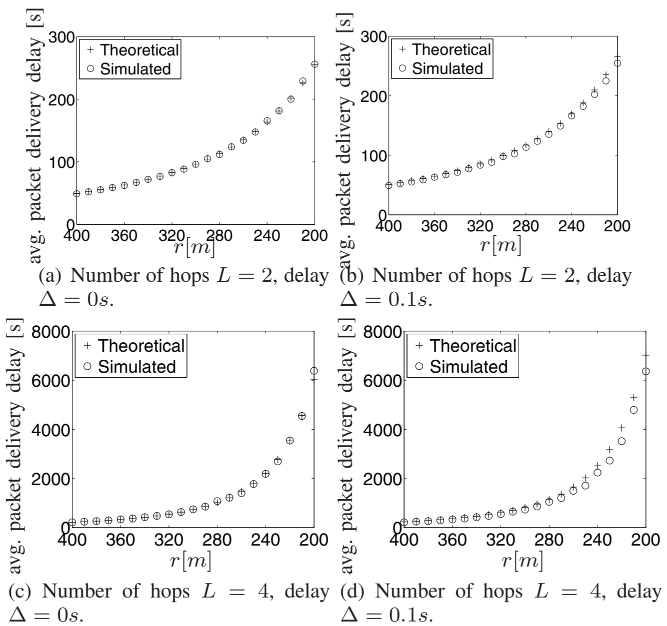
Figure 3 shows the comparison of theoretical and simulated curves of the IP-like average packet delivery delay. When the number L of hops increases, the delivery delay increases exponentially. This can be realized also from the shape of the curves in Figure 3(c)-(d). Differently from the DTN case, an increase in the sum Δ of transmission and propagation delays heavily impacts on the average delivery delay. For $L = 2$ and $r = 200m$, the difference between the cases $\Delta = 0.1s$ and $\Delta = 0s$ is about $10.6653s$, but for $L = 4$ becomes about $997,98s$, in contrast $2.7406s$ for DTN. Each point of the simulated curves in the Figures 2 and 3 is the result of the average of 5 simulation runs, each referred to a scenario of $500000s$. The simulations are performed on a high-performance computing platform for a total run-time of about 4 hours.

In summary, the following can be noted: for an increasing number L of hops and a decreasing value of the transmission



(a) Number of hops $L = 2$, delay $\Delta = 0s$. (b) Number of hops $L = 2$, delay $\Delta = 0.1s$. (c) Number of hops $L = 4$, delay $\Delta = 0s$. (d) Number of hops $L = 4$, delay $\Delta = 0.1s$.

Fig. 2: Comparison of theoretical and simulated curves of the DTN average packet delivery delays for different values of transmission radius r, number L of hops, and Δ.



(a) Number of hops $L = 2$, delay $\Delta = 0s$. (b) Number of hops $L = 2$, delay $\Delta = 0.1s$. (c) Number of hops $L = 4$, delay $\Delta = 0s$. (d) Number of hops $L = 4$, delay $\Delta = 0.1s$.

Fig. 3: Comparison of theoretical and simulated curves of the IP-like average packet delivery delays for different values of transmission radius r, number L of hops, and Δ.

radius r, in the ICN scenarios the DTN approach dramatically outperforms the IP-like one. In most cases the simulated curves are practically overlapped to the theoretical ones. This is due to the ergodicity [13] of the underlying continuous-time Markov chain of the two models. The maximum relative error in the results presented is referred to the IP case, $L = 2$, $\Delta = 0.1s$ and $r = 200m$ is below 6.5%.

IV. Discussion

We have proposed a model to evaluate and compare theoretically the average packet delivery delays in ICNs when either the IP-like paradigm of traditional TCP/IP protocols or DTN are adopted. We have provided numerical results obtained by applying our theoretical results to a scenario, in which we have specified the speed, the mobility model, and the transmission radius of the nodes. Our results confirm and address quantitatively the fact (realized experimentally in various works) that, when the network experiences a high degree of disruption, DTN outperforms the IP-like paradigm in terms of lower average packet delivery delay. We have focused on the case of an L-hop network topology modelling a single source-destination path. Extensions of our model to the case of multiple paths (e.g., nodes organized in layers) are among the subjects of our ongoing research.

References

[1] K. Fall, "A delay-tolerant network architecture for challenged internets," in *Proc. 2003 ACM SIGCOMM Conf. on Applications, Technologies, Architectures, and Protocols for Computer Communications*, pp. 27–34.

[2] R. Groenevelt, P. Nain, and G. Koole, "The message delay in mobile ad hoc networks," *Performance Evaluation*, vol. 62, no. 1-4, pp. 210–228, 2005.

[3] H. Zhu, L. Fu, G. Xue, Y. Zhu, M. Li, and L. Ni, "Recognizing exponential inter-contact time in vanets," in *Proc. 2010 INFOCOM*, pp. 1–5.

[4] M. Khabbaz, C. Assi, and W. Fawaz, "Disruption-tolerant networking: a comprehensive survey on recent developments and persisting challenges," *IEEE Commun. Surveys Tutorials*, vol. 14, no. 2, pp. 607–640, 2012.

[5] R. Durst, P. Feighery, and K. Scott, "Why not use the standard Internet suite for the interplanetary Internet?" California Institute of Technology, Tech. Rep., 2000.

[6] J. Ronan and C. O'Connor, "A further comparison of different TCP/IP and DTN protocols over the D-star digital data mode," in *Proc. 2011 ARRL and TAPR Digital Communications Con.*, pp. 72–79.

[7] C. Caini, H. Cruickshank, S. Farrell, and M. Marchese, "Delay- and disruption-tolerant networking (DTN): an alternative solution for future satellite networking applications," *Proc. IEEE*, vol. 99, no. 11, pp. 1980–1997, 2011.

[8] Z. J. Haas and T. Small, "A new networking model for biological applications of ad hoc sensor networks," *IEEE/ACM Trans. Networking*, vol. 14, no. 1, pp. 27–40, Feb. 2006.

[9] T. Matsuda and T. Takine, "(p,q)-epidemic routing for sparsely populated mobile ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 5, pp. 783–793, June 2008.

[10] A. Vinel, "3GPP LTE versus IEEE 802.11p/WAVE: which technology is able to support cooperative vehicular safety applications?" *IEEE Wireless Commun. Lett.*, vol. 1, no. 2, pp. 125–128, 2012.

[11] J. Isento, J. Rodrigues, J. Dias, M. Paula, and A. Vinel, "Vehicular delay-tolerant networks: a novel solution for vehicular communications," *IEEE Intelligent Transportation Systems Mag.*, vol. 5, no. 4, pp. 10–19, 2013.

[12] R. W. Wolff, "Poisson arrivals see time averages," *Operations Research*, vol. 30, no. 2, pp. pp. 223–231, 1982.

[13] J. R. Norris, *Markov Chains*. Cambridge University Press, 1998.

[14] M. Abdulla and R. Simon, "Characteristics of common mobility models for opportunistic networks," in *Proc. 2007 PM2HW2N*, pp. 105–109.